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SWITCHING ROOM ACOUSTICS WITH CAUSALITY-DRIVEN DUAL-FUNCTION PASSIVE METAMATERIALS FOR BROADBAND SOUND ABSORPTION AND DIFFUSION

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ABSTRACT

Acoustic metamaterials offer unique capabilities for achieving exceptional performance at low frequencies with compact designs. However, many existing designs focus on single-function applications, leaving a need for multi-functional solutions. To address this, we propose a Dual-Function Passive Acoustic Metamaterial (DFPAM) that integrates sound absorption and diffusion within the same structure by applying principles of causality and passivity. The DFPAM delivers broadband performance with excellent sound absorption ($<\alpha>= 0.85$) and diffusion ($<\delta>= 0.8$) over 1 octave and a half each, i.e., 400-1100 Hz for absorption and 1000-2500 Hz for diffusion. With a compact thickness of 12 cm-nearly half the size of traditional treatments-it efficiently uses space (1/3 for absorption, 2/3 for diffusion) while optimizing the performance of each state. Importantly, it mitigates the trade-offs often associated with combining these two acoustic mechanisms. This solution offers significant potential for room acoustics and environments where space is at a premium. By addressing multi-functional requirements with dual efficiency, The DFPAM offers transformative possibilities for room acoustics and can be adapted to diverse environments where multi-functional acoustic solutions are in increasing demand.

Keywords: *absorption, diffusion, hybrid materials, metamaterial, passivity*

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1. INTRODUCTION

Most existing acoustic metamaterial solutions remain configuration-dependent, addressing either sound absorption or diffusion, but rarely both. Hybrid solutions attempting to integrate these functions have often been constrained by physical and spatial trade-offs, leading to suboptimal performance.

In this work, we adopt a causality-driven approach to design a Dual-Function Passive Acoustic Metamaterial (DFPAM) that optimizes both absorption and diffusion within a single structure.

2. DESIGN PRINCIPLE

Absorption and diffusion of acoustic waves are contrastive effects as the former needs to dissipate the acoustic energy and the latter needs to scatter the waves with minimal dissipation. In the present case, we intend to use a strategy based on rigidly-backed slits loaded by an array of Helmholtz resonators as shown in Fig. 1(a).

By analyzing the sum rule given by the passivity/causality conditions of the acoustic system accounted for in this work, it is possible to evaluate the optimal value of the absorption-to-diffusion surface area ratio, $\phi_{\alpha|\delta}$, with a given target absorption spectrum. A depth of 12 cm is chosen in order to provide a solution that fits within dimensions similar to other metamaterial designs reported in the literature. It follows that $\min\left(\phi_{\alpha|\delta}\right) \approx 0.33$. Starting from a 3×3 square grid for the quarter of unit-cell with a combinatorial ratio of absorption cells to overall cells $\phi_\alpha = 1/3$, there are a total of 84 possible combinations. Due to mirror symmetries and further physical considerations regarding the choice of tesselation pattern and diffusion optimality, the rhombus depicted in Fig. 1(a) happens to be one of the best candidates available for sound diffusion. We finally make use of non-linear constrained minimization algorithms for maximizing both absorption and diffusion as well as determining their respective geometries. Figures 1(b-c) display the analytical, numerical and experimental sound diffusion and absorption coefficients obtained throughout this study. The DFPAM achieves high broadband sound absorption ($<\alpha>\approx 0.85$) and diffusion ($<\delta>\approx 0.8$), covering more than one octave in each configuration. For more details, the reader can refer to [1].

3. CONCLUSION

In this work, we present a dual-function metasurface capable of achieving high values of absorption, $<\alpha>= 0.85$, and diffusion, $<\delta>= 0.8$, for different broadband frequency ranges covering more than one octave in each configuration, i.e., $\Delta\alpha = [400, 1100]$ Hz, and $\Delta\delta = [1000, 2500]$ Hz, while still maintaining compact dimensions.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

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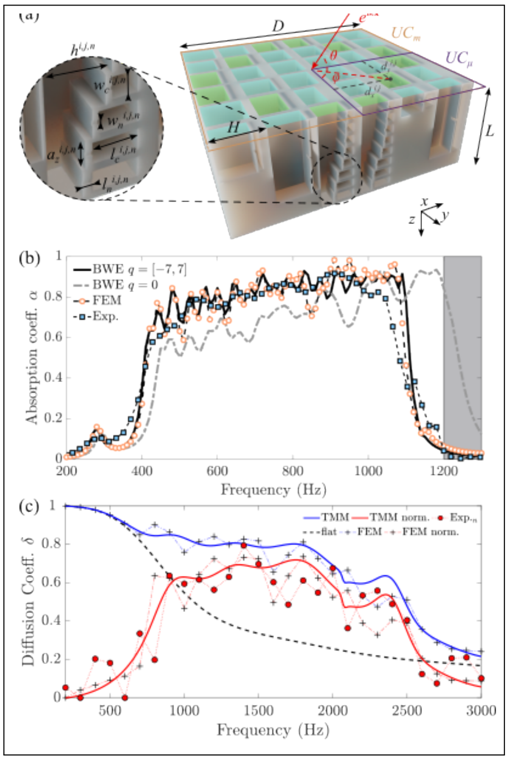

Figure 1. (a) 3D visualization of the DFPAM of side width $D = 30$ cm and depth $L = 12$ cm, with highlights on the micro unit cell (violet), used for absorption measurement in a square impedance tube and the overall macro unit cell (orange), which is formed by two-fold mirror symmetry. (inset) Geometrical parameters of the $(x, y) \rightarrow (i, j)$ slit for the n-th slit resonator section of height h and depth a_z. (b) Analytical, numerical and experimental absorption coefficients overlayed with those of each individual slits. (c) Analytical, numerical and experimental frequency-dependent diffusion coefficient $\delta(\omega)$.